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THE RELATION OF DOMAIN PEHNOMENA AND CRYSTAL ORIENTATION TO DESIGN AND THE USE OF MAGNETIC MATERIALS

L. J. Dijkstra
Westinghouse Electric Corporation
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WRIGHT AIR DEVELOPMENT CENTER

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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Dr. L. J. Dijkstra of the Research Laboratories, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, on Air Force Contract No. AF 33(616)-309, under RDO No. 477-651, "Magnetic Materials". The work was administered under the direction of the Aeronautical Research Laboratory, Directorate of Research, Wright Air Development Center, with Captain Ronald E. Sellers, Jr. acting as project engineer.

The present work is part of a continuing program on understanding the technically important magnetic properties of commercial magnetic material. The contribution of this present work is an understanding of the differences in the magnetic behavior of oriented sheet measured along different directions.

ABSTRACT

A review is given of the standard interpretation of the effect of grain oriented structures on magnetic behavior. It is found that this standard interpretation is not sufficient to explain all the details of the magnetization curves. In particular, a comparison of the magnetization curves taken in different directions in an oriented sheet reveals anomalies which cannot be understood by the standard theory. It is shown that these anomalies may be readily understood when due consideration is given to the properties of domains.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Leslie B. Williams

LESLIE B. WILLIAMS
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

THE RELATION OF DOMAIN PHENOMENA AND CRYSTAL ORIENTATION TO DESIGN AND THE USE OF MAGNETIC MATERIALS

In recent years, grain oriented magnetic materials have gained an important position in the field of soft magnetic alloys. The term "grain oriented" simply expresses that in the majority of the grains the crystallographic axes are oriented along certain directions in the sheet with only small deviations. To develop these grain oriented structures requires special metallurgical techniques. By a very carefully controlled process of rolling and heat treatment it is possible to produce in certain magnetic alloys textures which exhibit a very high degree of crystal orientation. This orientation leads to very desirable magnetic properties and as a result, grain oriented magnetic alloys are successfully being used in an increasing number of technical applications. For example, in power transformers where a high permeability is required at high values of the induction, grain oriented Si-Fe sheet steels have proven to be superior to hot-rolled non-oriented Si-Fe steels. This is clearly illustrated in Fig. 1-a in which the B-H curves for an oriented and a non-oriented Si-Fe electrical sheet steel are drawn for comparison.

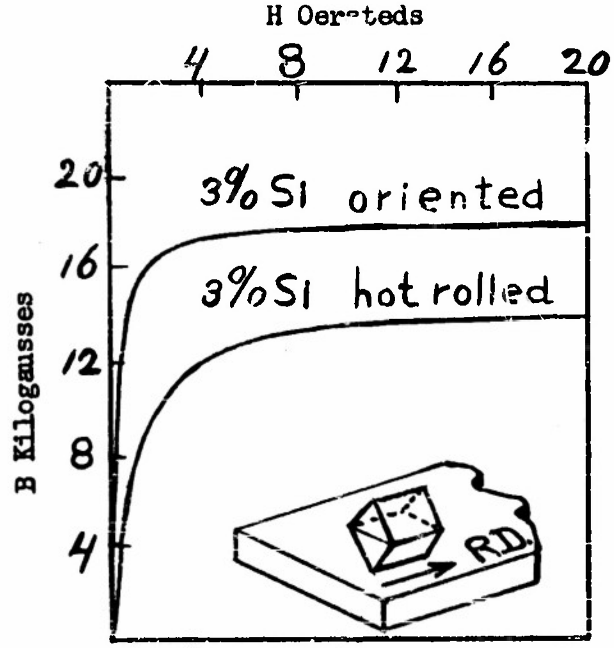

FIG. 1-a

Magnetization Curves for an Oriented and a Non-oriented Si-Fe Electrical Sheet Steel.

Grain oriented 50 Ni-50 Fe alloys with their rectangular hysteresis loop and relatively high value of the saturation induction are suitable core materials for use in magnetic amplifiers, computers, mechanical rectifiers, and similar devices. Fig. 1-b shows examples of the hysteresis loop for an oriented and non-oriented 50 Ni-50 Fe alloy sheet. In all these grain oriented alloys, superior magnetic qualities exist only if the flux is allowed to travel along certain directions in the sheet, usually the rolling direction (R.D.).

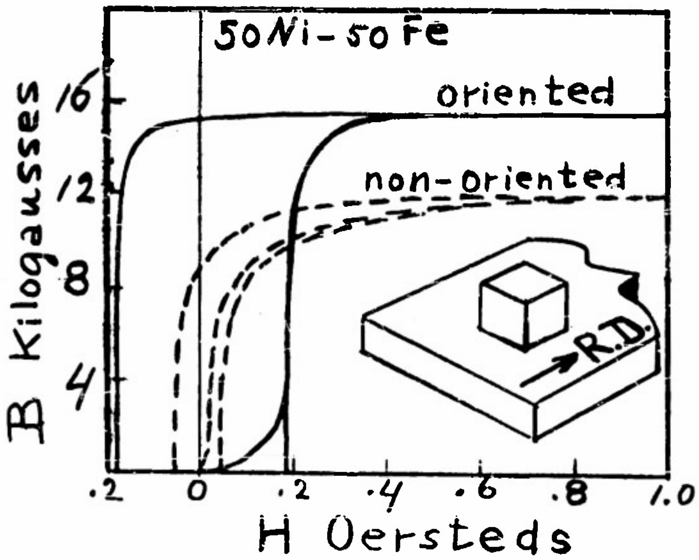

FIG. 1-b

Hysteresis Loop for an Oriented and Non-oriented
50 Ni-50 Fe Alloy Sheet

To understand the effect of grain orientation on the magnetic properties one can follow two ways. One way is the phenomenological way of approach. It has long been known that the ease of magnetization in a magnetic field H depends on the orientation of the field with respect to the crystal axis. This orientation dependence is commonly known as magnetic anisotropy. Fig. 2-a shows the magnetization curves along the principal crystallographic directions for a single crystal of 3.8% Si-Fe, Fig. 2-b, the corresponding curves for low inductions.

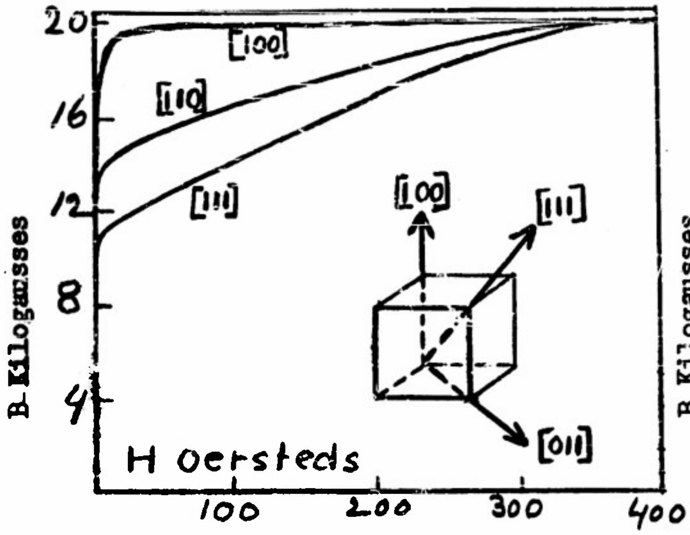

Fig. 2-a

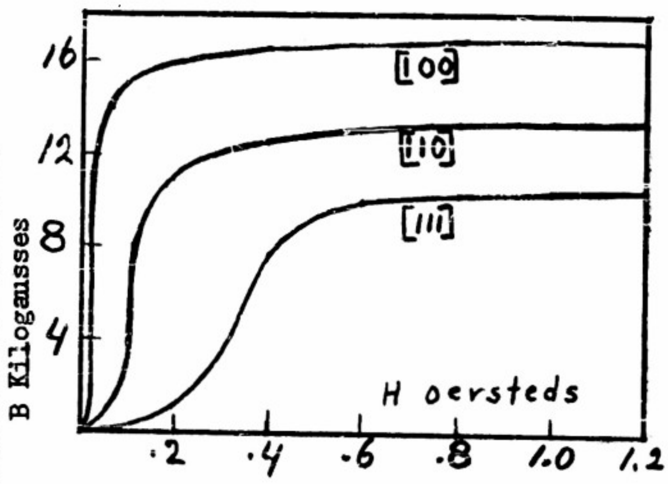

Fig. 2-b

FIG. 2-a. Magnetization Curves for a Single Crystal of 3.8% Si-Fe Along the Principal Crystallographic Directions.
FIG. 2-b. Same Curves for Low Induction.

The data were measured by Williams(1) on very pure specimens cut from single crystals in the form of a "picture frame" with closed magnetic circuit and the sides parallel to the desired crystallographic direction. The significant fact shown by these data is that along the (100) directions (the cube edges) the B-H curve is very steep. Almost complete saturation is reached in a relatively low field and these directions are therefore called easy directions of magnetization. Along the (111) and (110) directions (cube and face diagonals respectively) approach to saturation is much slower. They are hard directions of magnetization. The B-H curve along the (110) direction is intermediate between both the others not only for high induction above the knee but also for low induction as can be seen in Fig. 2-b.

Fig. 2 suggests that a sheet material with high permeability at high inductions can be achieved by orienting the grains with an easy axis of magnetization parallel to the direction in the sheet along which the flux has to travel. Two types of textures are of technical interest.

The "cube on edge" orientation shown in Fig. 1-a has the (001)-axis along R.D. and a diagonal plane in the plane of the sheet. The familiar example of this type of texture is the grain oriented 3% Si-Fe sheet steel, known under the trade names Hipersil, Trancor X, 3X and others. In this material about 80-90% of the grains have the desired cube on edge orientation with a spread in alignment of only a few degrees. Fig. 3 shows the typical B-H curves of this material measured along (100) (R.D.), along (011) (cross direction C.D.) and along (111) (55° to R.D.).

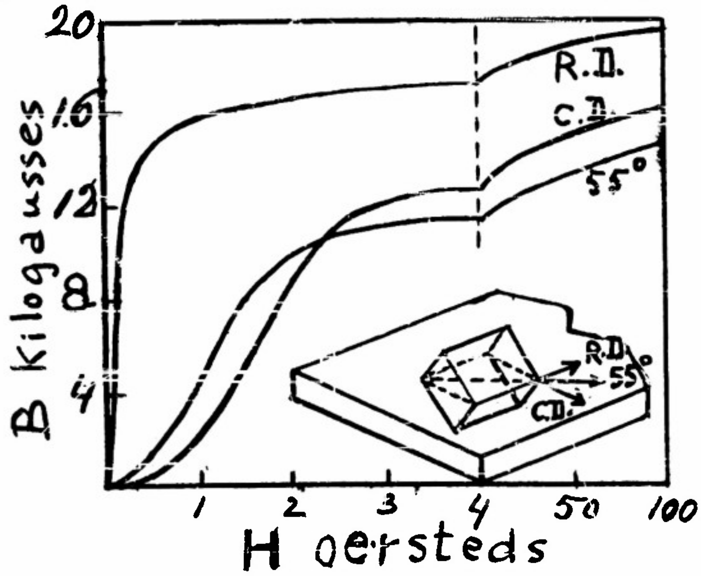

FIG. 3

Magnetization Curves for an Oriented Si-Fe Sheet Measured Along the Rolling Direction, the Cross Direction and at 55° to the Rolling Direction.

The superior quality for high inductions of the grain oriented material along R.D. compared with a non-oriented steel was already illustrated in Fig. 1-a. In Fig. 4, the permeability μ is plotted as a function of orientation in the sheet both for a grain oriented and a non-oriented material together with the single crystal data of Fig. 2. It clearly demonstrates the effect of orientation of the magnetic properties. The general trend of the permeability as a function of orientation is, at least for high inductions, qualitatively the same for the oriented sheet and the single crystals. For intermediate and low inductions this is no longer true, for the B-H curves along (110) and (111) have reversed their position in the oriented sheet compared with the single crystals. The initial permeability μ_o shows a pronounced minimum along (110) for the oriented sheet but along (111) for the single crystals. This reversal in anisotropy is not fundamental. However, for an explanation, the second way of approach in terms of magnetic domains appears to be more suitable.

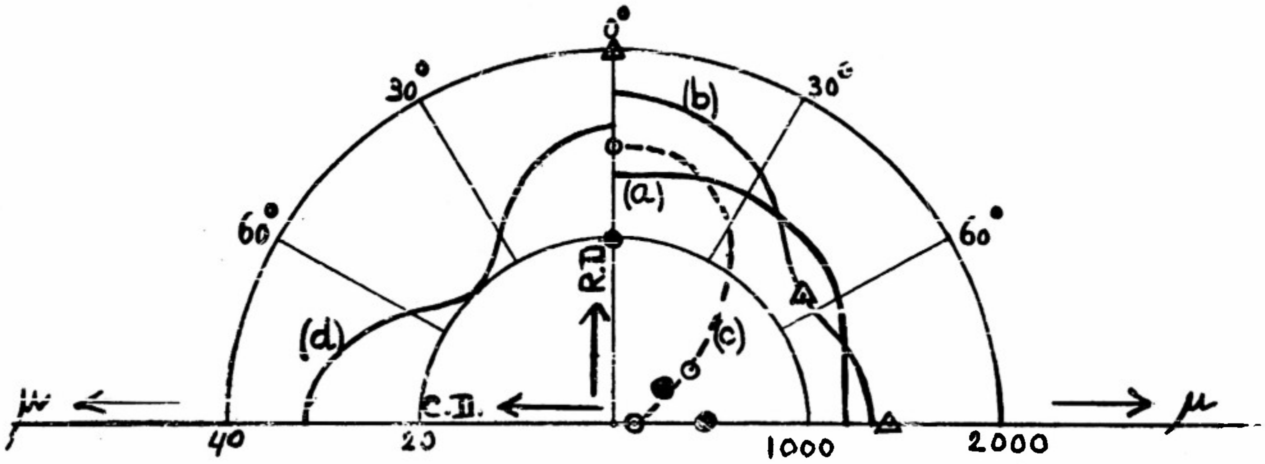

FIG. 4

Graph of Permeability

(a) Non-oriented Si-Fe, H=10.
(b) Oriented Si-Fe, H=10.
△ Single crystals, H=10. (after Williams).
(c) Calculated curve of μ_o for oriented Si-Fe.
⊙ Experimental points.
● μ_o of single crystals (after Williams), multiply μ scale by 6.
(d) Oriented 50 Ni-50 Fe, medium field.

A second familiar type of texture is the "cube on face" texture in which a cube face of the crystal coincides with the plane of the sheet, which therefore contains two (100)-directions. This type of texture with these two (100) directions parallel to R.D. and C.D. (Fig. 1-b) can be developed in all Ni-Fe alloys containing more than 30% Ni if the proper rolling and heat treatment technique is used. Of special interest are the alloys around the composition 50 Ni-50 Fe where the saturation induction shows a maximum. These oriented alloys are commercially known as Hipernik V, Orthonik, Deltamax, HCR and 5000 Z. Single crystal measurements have shown that as in the case of Si-Fe alloy the (100) axes are easy directions of magnetization. The B-H curve along this direction is nearly rectangular. It differs from the Si-Fe alloy in that the anisotropy is much less pronounced. Saturation along the hard directions, (110) and (111) is approached in a relatively low field below 50 oersteds. Examples of the hysteresis loop for a grain oriented 50 Ni-50 Fe alloy measured along R.D. and for a non-oriented alloy of the same composition, were already shown in Figure 1-b. The degree of orientation in this alloy can be made more perfect than in the Si-Fe alloy which causes the nearly rectangular shape of the hysteresis loop for the oriented alloy. Along C.D. the properties should be the same(2) (see Fig. 4) and for transformer cores it is therefore possible to use E or U shaped punchings.

Thus we see that the superior magnetic quality of the grain oriented alloys at high inductions are readily understood with reference to Fig. 2 and to what has been said about the texture of these alloys. It should also be clear why the superior qualities only exist if the flux path is along R.D. (or also along C.D. in 50 Ni-50 Fe). The commercial success of these grain oriented alloys, however, is not solely due to the effect of orientation. It is well known that the presence of impurities and microstrains is very detrimental to the permeability and hysteresis losses, and an important factor in the fabrication process of these alloy sheets is the proper heat treatment to keep impurities and strains to a satisfactory minimum.

Considerably more insight into the nature of the magnetic properties can be obtained if one describes the phenomena in terms of magnetic domains.(3) The basic concept of domain theory is that each crystal in a ferromagnetic material is subdivided into small regions called magnetic domains, schematically illustrated in Fig. 5.

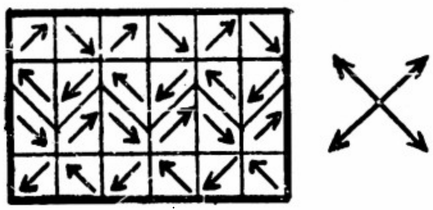

FIG. 5

Schematic Domain Structure

In each domain, the substance is magnetized to saturation with the magnetization vector I_s in a definite direction. This direction, which is different for neighboring domains, is not arbitrary in space. From magnetic torque measurements [3], e.g., we know that in a 3% Si-Fe alloy the system is in stable equilibrium if the magnetization I_s is along one of the six (100)-directions. We know the same is true for a 50 Ni-50 Fe alloy. These directions are called preferred directions of magnetization. An external magnetic field of certain strength is required to rotate the magnetization I_s out of the preferred directions into any other direction. For the Si-Fe alloy, a field of about 400 oersteds is necessary for rotation into the (111) and (110) directions; for the 50 Ni-50 Fe only a field of about 10 oersteds is needed.

Of great significance for magnetization processes are the transition regions between neighboring domains. These so-called domain walls have a finite thickness, which depends on the type of material and which for our alloys is of the order of 10^{-5} cm. Traversing the domain wall perpendicular to its plane, the magnetization vector gradually rotates from one preferred direction into another, thereby remaining parallel to the plane of the domain wall. This means that along the intersection of domain wall and specimen, stray flux is emerging into air. The standard magnetic powder technique(3) for observation of domain structures is based on this effect. Figure 6 shows an example of a magnetic domain pattern in the unmagnetized state in a grain oriented 3% Si-Fe sheet. Domain walls and the direction of the magnetization in the various domains are parallel to R.D. as indicated in Figure 7-e.

The domain wall area is a seat of energy; for, as pointed out, inside the wall the magnetization vector I_s is not along a preferred direction. This energy can be calculated and is usually of the order of 1 erg per cm^2 wall area. The plane of the wall tends to make equal angles with the flux closure across the surface of the domain wall.

Since we saw that domain walls are a seat of energy, the fact why multi-domain structures exist needs some further explanation. The argument usually runs as follows. Fig. 7-a shows a single crystal which is magnetized along a preferred direction and represents a single domain configuration. The flux leaves the upper face, travels through air and enters the lower face, which means the system represents a certain amount of magnetostatic energy. Figure 7-b shows a two-domain structure in which much shorter flux path through the air is achieved at the cost of a certain amount of wall energy. In Figure 7-c, assuming one preferred axis is parallel to the upper edge, complete flux closure has been obtained by a quadruple domain configuration, which has only wall energy.

FIG. 6. Domain Pattern in an Oriented Si-Fe Sheet.

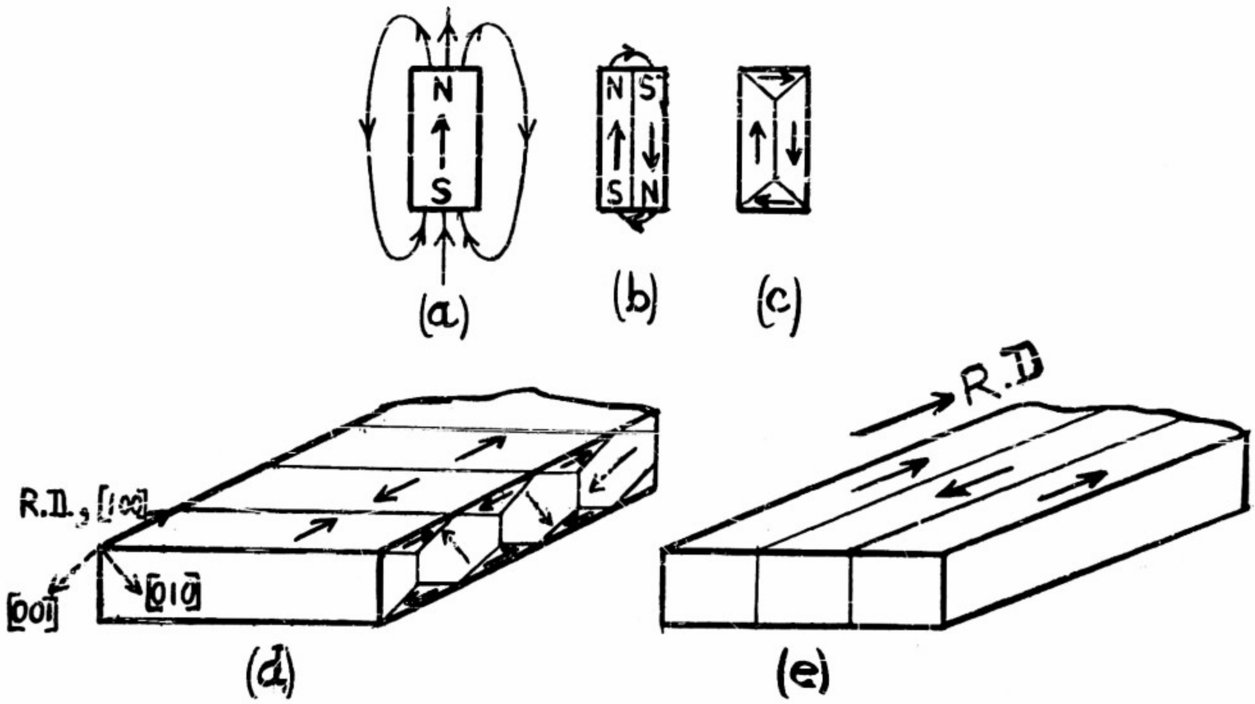

FIG. 7

Possible Domain Configurations in Oriented Materials

In the general case, it turns out that the situation sketched in Figure 7-b or 7-c is energetically more favorable than the one in Figure 1-a. Similar conditions govern the domain structure in our grain oriented materials. Stray flux will appear at the surface of the sheet and at grain boundaries and edges due to imperfect alignment of the grains. This stray flux can be reduced by the formation of, e.g., anti-parallel domains as illustrated in Figure 7-b.

In the unmagnetized state, the distribution of the domains over the six preferred directions in a cubic metal is such that there is no bulk magnetization. This can be realized in many ways, but the actual domain structure will be the one for which there is a balance between the various energy terms, of which we mentioned the magnetostatic energy and the wall energy. A very important factor in governing the domain structure is the orientation of the crystal axis either with regard to internal surfaces like grain boundaries or external surfaces, since this orientation determines the amount of stray flux appearing at this surface. It is, therefore, not surprising that the special crystal orientation with respect to the plane of the sheet found in grain oriented alloys is reflected in their domain structure. The type of domain structure which can be considered as representative of the "cube on edge" texture with preferred direction along the edges as found in the oriented Si-Fe alloy was reproduced in Fig. 6. It consists of anti-parallel domains magnetized along the (100) axis (R.D.) in the plane of the sheet. The domain walls are generally continuous across grain boundaries between well aligned grains to realize flux closure. The spacing of the domains is determined by the degree of alignment between grains and with respect to the sheet surface and by dimensional factors like sheet thickness and grain size.

The larger these dimensions and the more perfect the alignment, the wider the spacing. (A competitive domain configuration is pictured in Figure 7-d, consisting of anti-parallel (010) or (001) domains and flux closure (100) domains along the surface. Normally this structure has a higher energy partly due to the larger wall energy, but can become more stable than the former if mechanical strains are present.[4])

Attempts to observe domain patterns in the "cube on face" oriented 50 Ni-50 Fe alloy by the magnetic powder technique have been unsuccessful. This does not mean that domains do not exist. Failure has been attributed to the weak gradient of the stray fields. Whatever the precise domain structure in this alloy sheet in the unmagnetized state may be, it should consist of domains magnetized along the two preferred directions in the plane of the sheet, R.D. and/or C.D. Domains magnetized along the cube axis perpendicular to the sheet in a structure similar to that in Figure 7-d do not occur for the same reason as mentioned for the "cube on edge" texture.

If an unmagnetized specimen is placed in a magnetic field, it becomes magnetized. Magnetization is possible according to two different processes.

A. By lateral displacement of the domain walls:

Domains which are favorably oriented with respect to the field grow at the expense of adjacent less favorably oriented domains. If a sufficient field is applied along a preferred direction, e.g., the (100)-axis in Figure 6, part of the domains grow and others disappear until only one large domain remains and the crystal is magnetized to saturation in the field direction. The magnetization process is then complete. The main obstacles impeding the displacement of the walls are impurities and microstrains. If both these are kept low, this mechanism of magnetization is very easy and does not require a high field, for example, about .1 oersted or lower. Domain wall displacements are predominant along the B-H curve for the (100) directions of the single crystal in Fig. 2 and also along the B-H curve below the knee measured along R.D. in the grain oriented alloy sheets. The easy directions of magnetization thus find a natural interpretation in terms of magnetic domain wall displacements.

B. By domain rotation:

Normally the two processes A and B are well separated along the B-H curve since for rotation usually much higher fields are required. In the general case in which the applied field is not parallel to an easy direction, initial magnetization occurs mainly by wall displacement until each grain is practically a single domain magnetized to saturation along the easy direction closest to the field direction. Further magnetization occurs by rotation of the magnetization vector out of this easy direction into the field direction against the crystal forces which tend to align it along a preferred direction. This rotation process corresponds to the part of the B-H curve above the knee in Figures 1 and 2 and requires, as already mentioned, a much larger field for completion. The significance of the orientation procedure of the grains in a polycrystalline sheet is, therefore, simply that domain rotations are practically eliminated.

Several details in the foregoing paragraphs are readily explained in terms of domains. In the case of the B-H curve in Figure 3 measured along C.D., none of the existing domains has (assuming ideal alignment) a component of magnetization along the direction of the field. In very low fields, therefore, only rotation of the magnetization out of R.D. into C.D. occurs. The initial permeability $\mu_{o,C.D.}$, therefore would be expected to be of the order of the slope of the (110) curve above the knee in Fig. 2-a, which is about 30. Actually we find from Fig. 4 a value equal 100. The difference, no doubt, is caused by imperfect alignment of the grains. (The steeper part of the curve must be explained as a transition from the simple structure in Fig. 7-e to a more complicated one of the type sketched in Fig. 7-d. The measured value for the initial permeability $\mu_{o,R.D.}$ along R.D., which is practically due to domain wall displacements, is equal to 1500. To estimate the initial permeability $\mu_{o,55^o}$ at 55^o to R.D., we realize that the magnetization occurs practically along R.D. and is equal $\mu_{o,R.D.} H \cos 55^o$, which yields for $\mu_{o,55^o}$ the value $\mu_{o,R.D.} \cos^2 55^o = 500$.

Actually measured is a value of 450-500. This explains the reversal in position of the B-H curves along (110) and (111) for low induction in Fig. 3 compared to Fig. 2-b.* Even for intermediate fields as high as 2 oersteds the inversion is apparent. The effect is not fundamental but simply a result of a difference in domain structure.

Are there ways to further improve the magnetic quality of these grain oriented materials? One way of attack is to lower the amount of impurities and microstrain by improved heat treatments, resulting in lower losses and an increase of permeability. It also may be of some importance to develop an electrical sheet steel with the cube on face orientation for use in rotating machinery where the flux has to travel along different directions in the sheet. Another logical way which leads to further improvement seems to be to perfect the alignment of the grains, especially in the 3% Si-Fe alloy in order to square up the hysteresis loop still further so as to obtain higher permeability at high inductions. A more perfect alignment, however, means theoretically a wider spacing of the domains since the amount of stray flux at the surface along grain boundaries and edges is reduced. This in itself is an unfavorable factor in the initial permeability and will also lead to an increase in anomalous losses.

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* The B-H curves in Fig. 2-b were measured on three different single crystals. The difficulty of having no domains with a component parallel to the field does not exist here. (See Ref. 3, Page 558).

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